REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1999	Final Report

4. TITLE AND SUBTITLE

Studies of Plasma Instability Processes Excited by Ground-Based High Power HF ('Heating') Facilities

5. FUNDING NUMBERS

F6170896W0146

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC 96-4009

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking P. N. Lebedev Physical Institute as follows: The contractor will conduct an interactive test of theory and data to quantitatively compare the Gurevich theoretical calculations driven by measured input boundary conditions to existing data. They will design and implement experiments to iterate comparison of refined experiment to refined theory. They will collect an initial set of data at Arecibo theory. The theory, the incoherent scatter radar data, and supporting observations will be used to pursue electron acceleration mechanisms. The deliverables will be the feasibility study and a final report detailing al the findings.

14. SUBJECT TERMS

EOARD, Physics

15. NUMBER OF PAGES

9

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

SUMMARY
GRANT EOARD and AFOSR /2310G9

Studies of Plasma Instability Process Excited by Ground Based High Power HF (Heating) Facilities

The two main objective of the first year of the project were the studies:
a) of the formation of field aligned small scale striations with their effect on SEE emission,
b) energization of electrons along with their relationship to excite optical emission.
During this year the following main results are obtained :

1. The theory of airglow induced by strong electron heating inside striations is developed. The comparison with existing observations shows that the $O(^1D)$ red line emission is well explained by the theory. For the $O(^1S)$ green line emission the observational results are strongly fluctuating and could be significantly higher, than calculated for the theory, what indicates that the electron acceleration is also essential for the production of green line airglow.

2. The theory of incoherent scattering from the modified ionosphere in the presence of field aligned striations is developed. It is shown that the best fit for the ion line autocorrelation function (ACF) gives the value of electron temperature T_e much less both the maximal and average electron temperature inside striations. This result agrees well with usually observed modest level in electron heating. On the other hand it is shown that the standard error, in ACF fitting induced by the existence of a strongly heated striations is much higher than the standard error, what could be used for the measurements of the strong T_e enhancement inside striations.

3. The theory of parametric decay of upper hybrid (UH) plasma waves into low hybrid (LH) wave and UH wave with shifted frequency is developed when both pump and decay UH waves are trapped inside striations. It is shown that exactly this process is responsible for the generation stationary SEE emission. Both main features of SEE spectrum the down shifted maximum and long continuum tail are obtained in agreement with observations. The conditions of excitation of the second and the third decay modes are established.

4. Several new effects which could be observed in ionospheric modification are predicted. A complex program for the measurements is proposed for the nearest observational campaign which is supposed to be in summer 1997 in Arecibo and Gorki.

ANNUAL REPORT
GRANT EOARD and AFOSR /2310G9

Studies of Plasma Instability Process Excited by Ground Based High Power HF (Heating) Facilities

The active Heating Experiments (ionospheric modification by ground based high power HF transmitters) were performed in the US, USSR and more recently in Western Europe for over two decades (Utlaut 1970, Utlaut and Cohen 1971, Carlson et al 1972, Gurevich 1978, Stubbe and Kopka 1982). Heating experiments were used to reach understanding of various physical, chemical and plasma processes in ionosphere and to develop a variety of engineering applications (see Gurevich 1978, Migulin and Gurevich 1984, Carlson 1990). Significant results had been obtained but much still remains to be learned. New more powerful Heating Facilities are now under construction by the US Air Force to further push the boundaries of our knowledge of these processes.

It was found that used in modification HF power is sufficient to excite different type of plasma instabilities (Carlson et al 1972, Perkins and Valeo 1974, Vaskov and Gurevich 1975). One of the most significant new physical phenomena, discovered during ionospheric modification was the resonance instability leading to generation of small scale striations which are plasma density depletions strongly elongated along the Earth's magnetic field (Utlaut 1970, Gurevich 1978). Recently such striations were also observed in experiments in situ on board rockets (Kelley et al 1995). They have been seen as essentially local stationary depletions of plasma density $|\delta N/N| \sim 0.05$ with scales of the order of 10 meters across and several kilometers along the magnetic field lines.

A nonlinear theory determining the conditions of existence and structure of stationary striations was recently developed (Gurevich et al 1995). The theory is in remarkably good agreement with the rocket observations (Kelley et al 1995). It's most significant prediction is a strong local enhancement of the electron temperature T_e in the striations. Maximal electron temperature in the center of striations can reach the values $T_e/T_i \sim 3 \div 5$, average temperature ratios in a strongly disturbed region can be of the order $T_e/T_i \sim 2 \div 3$. Gurevich and coworkers theory and recent analysis done by Carlson and coworkers (Mantas and Carlson 1996) showed that much of HF excited optical emission (previously attributed to electron acceleration) could come as a result of thermal accelerated electrons. Yet we still know from incoherent scatter radar plasma line data (Carlson et al 1982) that electron acceleration to well over 10 ev occurs.

That confronts two most outstanding problems in this field: the formation of field aligned small scale striations with their effects of SEE emission, anomalous absorption a.s.o. , and energization of electrons along with their relationship to excited optical emissions. The

objective of the first year of the project was theoretical investigation of these problems and experimental studies to quantitatively test and after that refine the theory.

1 Airglow enhancement

The airglow enhancement observations in ionospheric heating experiments (Biondi et al 1970, Haslett and Megill 1974, Sipler and Biondi 1978, Adeishvili et al 1978, Bernhardt et al 1988,1989,1991) have been usually considered as supporting evidence of electron acceleration by high power HF-waves.

Carlson and coworkers have recently shown the need of re-interpreting much past of the HF excited optical emission data as due to anexpectedly high electrons temperature (Mantas and Carlson 1996). They also have argued, based on experimental data, that this excited optical emission is sometimes spatially structured.

The objective of this section is to analyze the possibility of such a new interpretation of the results of airglow observations basing on the theoretical predictions of a strong local enhancement of electron temperature T_e inside striations (Gurevich et al 1995). The usually observed red (630 nm) and green (557.7 nm) optic emission is due to exciting of $O(^1D)$ and $O(^1S)$ levels what ask the minimal (threshold) energy of electrons 1.96 ev and 4.17 ev respectively. The maximal cross section for exciting the $O(^1D)$ and $O(^1S)$ levels occurs at 6.4 and 14 ev. Such high electron energies are difficult to reach since the ambient electron temperature in the F-region is about 0.1 ev. That is why the production of high energy suprathermal electrons due to acceleration by Langmuire waves was usually considered as a source of observed airglow (Bernhardt et al 1989, Gurevich et al 1985). Another possibility considering the tail of Maxwellian distribution as the source of energetic electrons was explored in our work.

As was established by the theory (Gurevich et al 1995) the effective heating of electrons inside the striations elongated along the directions of geomagnetic field, take place due to resonance instability in the resonance region of ionosphere between upper hybrid and Langmuire levels, when the amplitude of HF electric field exceeds a characteristic value $E_0 \sim 100mv/m$. We calculated the heating inside resonance region and demonstrated the effective broadening of the heated region due to electron thermal transport along magnetic field lines. Thus the strongly locally heated region with dimensions $5 - 10$ km along the geomagnetic field is established. The excitation rate of $O(^1D)$ and $O(^1S)$ electronic levels of atomic oxygen by the hot electrons inside striations is calculated. The results are compared with the detailed measurements by Sipler and Biondi (1972) and Haslett and Megill (1974). The comparison shows that the $O(^1D)$ emission at 630 nm is well explained by the theory of a strong electron temperature enhancement inside striations.

On the other hand for the $O(^1S)$ green line emission the observational results are strongly fluctuating and could demonstrate the observational values which are significantly higher, than calculated from the theory. That means that acceleration of electrons is also essential for the production of the airglow by high energy electrons $\varepsilon \geq 5 - 10$ ev.

A fundamental prediction of the theory is a strong diminishing of the artificial emission at the red line when the frequency of the heating wave f is close to the multiple resonance

of gyrofrequency f_B: $f \approx nf_B$, where $n = 3, 4, \ldots$.

The detailed results of the calculations are presented in the paper given in Appendix I of this report. The paper is published in Journal of Geophysical Research, v.102, N A1, 1997.

2 Measurements by incoherent scattering of a strong electron temperature enhancement inside striations.

Gurevich et al theory (1995) predicts a strong inhancement of electron temperature T_e inside striations. This theoretical predictions has not been yet confirmed. The measurements by incoherent scattering of the electron heating in ionospheric modification experiments often show a modest level of temperature ratios $T_e/T_i \leq 1.2 \div 1.3$ (Gordon and Carlson 1974, Honary et al 1995). It is important to remember, however, that in the analysis of the incoherent scatter measurements T_e is assumed to be constant in the scattering volume. The radial dimensions of this volume is 600m in Arecibo and 5 km in Tromsø, the lengths 150 — 600m. But according to the theory (Gurevich et al 1995) in the ionosphere, modified by radiowaves, the electron temperature can be strongly inhomogeneous, due to the existence of striations, with T_e/T_i changes of 3 — 5 to 1 on the scale of 10m.

The objective of this section is to consider the effective shape of the ion line spectra or its Fourier transform, autocorrelation function (ACF), when there are strong local electron temperature variations. The results of our calculations for the most perturbed situation when striations are packed closely together are shown in the Fig.2 (see Appendix II) where the spectral form of the ion plasma lines in the disturbed ionosphere is presented for different values of maximal electron temperature in the center of striations $T_m = T_e^{max}/T_i$. The value of T_m as is shown in Gurevich et al 1995 is growing with the power of heating wave. The best least - square fit for the ion line obtained for the homogeneously heated plasma gives the value T_e/T_i which is much less both the maximal and average electron temperature in striations. We see that ion plasma line does not give a real information about the electron temperature in locally heated plasma. It is easy to understand the physical reason of this effect: the input in ion plasma line from the strongly heated plasma $T_e/T_i >> 1$ is much less than from the cold one. It means that in the averaging the cold part would always dominate.

In practice, the ionospheric parameter estimation starts from a multiparameter fit of ACF for a model of homogeneous plasma. We produced the one parameter least - square fit of ACF in disturbed conditions, for a model of homogeneously heated plasma. The calculation of ACF for the disturbed conditions has been done at different values of the maximal temperature T_m. The parameter which has to be determined is as before the ratio of electron temperature to ion temperature T_e/T_i. The other parameters such as the ion temperature T_i, the electron density and the O^+ content are supposed to be known. The results show again that the determined value of T_e/T_i is significantly underestimated.

The analysis of the error appeared in the fitting procedure provides important information about ionospheric plasma state. In Vallinkovski, Lehtinen, 1990 a,b, such an analysis has been performed for the errors resulting from small variations of ionospheric parameters, but no regular structure has been supposed. In our case the strong local heating may be also treated as variation of plasma parameters. That is expected has to lead to substantial

increasing of the error obtained. We consider the deviation of the best fit and model ACF calculated for disturbed ionosphere. The dependence of the error obtained under fitting against maximal temperature T_m is shown in Fig.6 (see Appendix II). The deviation has been normalized on the standard error of the fitting $\Delta_r = 1\%$, (Vallinkovski, Lehtinen, 1990 a). We see, that at $T_m > 3$ the error induced by the regular inhomogeneous structure of T_e is much higher than the standard error and it is rapidly growing with T_m. These measurements of the induced error could be used to determine the existence of a strong heating of electrons inside striations. The other possibility to detect strong local heating appear in the analysis of the dependence of total power of scattered signal against temperature variation.

The detailed results of the calculations are presented in the paper given in Appendix II to this report. The paper is send for publication to Geophysical Research Letters.

3 Generation of SEE. Parametric decay of upper hybrid plasma waves.

According to the theory of resonance instability the creation of the striations is a result of the local heating of an anisotropic ionospheric plasma by upper hybrid plasma waves (UH) generated by the linear transformation of the pump heater wave on the striation density depletion (Vaskov,Gurevich 1975, Gurevich et al 1995). We see that the excitation of high level UH waves oscillations in the resonance region is deeply connected with the existence of the striations. Directly, the energy of the pump wave which goes to excitation of UH wave determines its strong anomalous absorption in the resonance region (Gurevich et al 1996). On the other hand highly excited UH wave through the decay processes generate UH waves with shifted frequencies what lead to the artificial emission of a wide spectrum of radio waves by the disturbed ionosphere (Stubbe et al 1984). This process known as stimulated electromagnetic emission - SEE is one of the most interesting and intensively studied in ionospheric experiments nonlinear phenomena. Some observed specific features of SEE spectrum and its dynamic behavior are found to be closely connected with the excitation of striations in the vicinity of multiple electron gyrofrequency (Leyser et al 1989, Stubbe et al 1994).

SEE undoubtedly contains a fundamental information about nonlinear processes proceeding in the ionospheric plasma under the action of a powerful electromagnetic wave. But to realize the physical meaning of these processes, to understand the language which ionosphere uses saying us about these nonlinear phenomena, the adequate theory should be developed.

This theory does not exist yet. In previous theoretical papers were used models which discussed processes in homogeneous plasma only (Leyser 1991,Grach Shvarts 1991,Zhuo et al 1994, Istomin and Leyser 1995). This allowed to obtain criterium for the beginning of the decay of UH wave into low hybrid wave (LH) and UH wave with shifted frequency or for other decay processes which are significant near multiple gyrofrequency region. But that gives only the possibility to have qualitative description of the main physical processes determining the SEE spectrum formation.

The real situation differs significantly from these models first of all because the decay processes are going in the strongly inhomogeneous plasma. The excitation of UH wave by

itself is determined by the existence of plasma inhomogeneities - striations. Excited UH waves are not free waves - they are trapped inside striations. The amplitudes of UH wave field and its height distribution is fully defined by the pump radio wave and the structure of striations through the process of exciting plasma inhomogeneities. Connection between UH wave field and pump wave is established recently by (Gurevich et al 1995) . It was shown that simultaneously with growth of the density inhomogeneity a strong heating of electrons inside the striations takes place: T_e becomes several times larger than the background value T_{e0}. This heating is due to a high plasma amplitude of UH wave excited inside striations. Thus, both plasma and UH wave distribution in the upper hybrid resonance region is strongly inhomogeneous.

To describe SEE emission the decay processes for UH wave in such an inhomogeneous plasma should be studied first of all. That is exactly the objective of this section. We consider here the decay of UH wave into the LH wave and downshifted UH wave inside inhomogeneous striation when both pump and decay UH waves are trapped. It should be emphasized that only trapped modes provide a possibility for the existence of an absolute instability in inhomogeneous media. Untrapped modes could be amplified passing through inhomogeneous media only (Perkins 1971). From that it follows that the stationary SEE emission is generated by UH waves trapped inside striations.

The important role in the process of parametric instability plays the leakage of UH wave into the Z - mode radiation. This process does not exist in homogeneous medium at all. But as it is shown directly leakage determines the value of a decay critical field E_c which due to this becomes significantly higher than critical field in homogeneous plasma. Further, differently from previous theories where UH wave with electric field $\vec{E}_1$ perpendicular to the Earth's magnetic field $\vec{B}$ were considered only we discuss the spectrum of any angles between $\vec{E}_1$ and $\vec{B}$, what allows taking into account striations height inhomogeneity to determine the main peculiarities of the spectrum of excited decay modes. That agrees well with the usually observed SEE spectrum. Both main features of SEE spectrum the downshifted maximum and long continuum tail are clearly seen in good agreement with observations. The conditions of excitation of the second and third decay modes are established also.

The following main results are obtained.

1. Coupled mode equations describing the decay process in inhomogeneous plasma are derived. Analytical solution of this equations is obtained in conditions when WKB approximation could be applied .

2. Critical field E_c and increment γ for decay instability are found for both the cases when the Z-mode radiation and when the electron collisions dominate. The first process does not exist in homogeneous medium at all. When the number of striations is not too large directly Z-mode leakage determine the value of decay critical field E_c, which due to this became significantly higher, than the critical field in homogeneous plasma.

3. The full width of the excited low frequency spectrum $f_h \approx 40 - 100$ kHz and the position of its characteristic maximum close to the first LH harmonic ($f_m \sim 10$ kHz) are determined. These results agree well with both main features: continuum and downshifted maximum of SEE emission.

4. Critical field for generation of the second and the third harmonics are determined. It is shown that the critical field is rapidly growing with the number of harmonics. So mostly

probable is the case of excitation of the first and second harmonics only. Excitation criterium for harmonics higher than the third is not reached in reality. This results are in agreement with the SEE emission spectrum also.

The detailed results of calculations in this section are presented in the papers in Appendix III to this report. The paper is accepted for publication in Physics Letters A, 1997.

4 Conclusion

Basing on the developed theory the following new effects in ionospheric modification are predicted:

1. A strong diminishing of the red line emission $O(^1D)$ at 630 nm when the frequency of the heater wave f comes close to the multiple gyroresonance nf_h is predicted .

This effect could be used to determine the relative role of the heating and acceleration of electrons in ionospheric modifications.

2. In the ISR measurements of electron temperature a substantial increase of the error in the mean square deviation of the ACF when the heater station is put on is predicted. This effect could be used to determine the existence of a strong heating of electrons inside striations.

3. The mean features of the plasma line in the spectrum of the HF radar when its ray is close to orthogonal to the Earth's magnetic field is predicted basing on the theory of parametric decay of upper hybrid waves. Both upshifted and downshifted plasma lines should have the wings of the order of 50 - 100 kHz and first pike at 10 - 12 kHz shift.

4. Due to selffocusing and Z-mode radiation, which depends significantly on the structure of group striations, we predict the patched structure of accelerated electrons in the plane orthogonal to magnetic field. This structure could be essentially affected by the electric drift of artificial ionospheric inhomogenieties.

5. The proposed program of ionospheric modification experiments at Arecibo should include the following simultaneous measurements.

a) Optic emission at 630 nm, 557.7 nm, 844.6 nm amd 777.4 nm what will make it possible to determine distribution function of superthermal electrons from 2 to 12 ev.

b) ISR measurements of electron plasma line in the higher than the resonance region, what allows to determine superthermal electron distribution in the energy range 10 - 16 ev (method of Carlson et al, 1982).

c) ISR measurements of all parameters and mean square fit errors including electron temperature (to determine the heating inside striations).

d) SEE emission measurements.

e) Plasma line measurements in the direction close to orthogonal to **B** by 50 MHz and 150 MHz radars. This data should be compared in details with presented in Appendix III theory and with observations of SEE spectrum.

f) Plasma line measurements by ISR at different heights. Space and time structures of accelerated electrons.

g) Special program for frequency changes of the heater wave near the third harmonic of electron gyroresonance. Detailed measurements of SEE emission, anomalous absorption,

airglow and plasma lines by ISR and HF radars in this frequency region.

6. The future development of our theoretical work would include

1) Testing the theory against of all new data of the described experiments which are supposed to be performed during the summer 1997.

2) Developing of the detailed theory for the electron acceleration process including the proposed new mechanism of acceleration by Z-mode in transformation region.

3) Developing the detailed theory of the spectrum of SEE emission and plasma line in direction orthogonal to geomagnetic field.

REFERENCES.

T.G.Adeishvili, A.V.Gurevich, G.M.Milikh et al. Sov.J.Plasma Phys. **4**, 721, (1978).

P.A.Bernhart, L.M.Duncan, C.A.Tepley Science **242**, 1022, (1988).

P.A.Bernhart, C.A.Tepley, L.M.Duncan J.Geophys.Res. **95**, 9071, (1989).

P.A.Bernhart et al. Geophys.Res.Lett. **18**, 1477, (1991).

A.A.Biondi, D.P.Sipler, R.D.Hake J.Geophys.Res. **75**, 6421, (1970).

H.C.Carlson, W.E.Gordon, R.L.Showen J.Geophys.Res. **77**, 1242, (1972)

H.C.Carlson, V.B.Wickwar, G.P.Mantas J.Atm.Terr.Phys. **44**, 1089, (1982).

H.C.Carlson EGARD EPP Symposium **1B**, 8113, (1990).

W.E.Gordon, H.C.Carlson Rad.Sci. **9**, 1041, (1974).

M.Grach, M.M.Shvarts, Proc. of the 3rd Suzdal Symp., Suzdal, ed. by V.V.Migulin, 89, Moscow (1991).

A.V.Gurevich Nonlinear Phenomena in the Ionosphere. Springer – Verlag, New York, 1978

A.V.Gurevich, A.V.Lukyanov, K.P.Zybin Phys.Rev.Lett. **75**, 2622, 1995.

A.V.Gurevich, Y.S.Dimant, G.M.Milikh, V.V.Vaskov Atm.Terr.Phys. **47**, 1057, (1985).

A.V.Gurevich, A.V.Lukyanov, K.P.Zybin Phys.Lett. A **211**, 363, (1996).

J.C.Haslett, L.R.Megill Radio Sci. **9**, 1005, (1974).

F.Honary, T.R.Robinson, T.B.Jones, P.Stubbe J.Geophys.Res. **100**, 21489, (1995).

Ya.N.Istomin, T.B.Leyser Physics of Plasmas **6**, 2084, (1995).

M.C.Kelly, T.L.Arce, J.Salowey et al. J.Geophys.Res. **100**, 17367, (1995).

T.B.Leyser, B.Thidé, H.Derblom, B.Lundborg, P.Stubbe, H. Kopka Phys.Rev.Lett. **63**, 1145, (1989).

T.B.Leyser J.Geophys.Res. **18**, 408, (1991).

G.P.Mantas, H.C.Carlson J.Geophys.Res. **101**, 195, (1996).

V.V.Migulin, A.V.Gurevich J.Atm.Terr.Phys **47**, 1181, (1984).

P.W.Perkins, J.E.Valeo Phys.Rev.Lett **32**, 1234, (1974).

F.W.Perkins, J.Flick The Physics of Fluids **14**, 2012, (1971).

D.P.Sipler, M.A.Biondi J.Geophys.Res. **83**, 1519, (1978).

P.Stubbe, H.Kopka et al. J.Geophys.Res. **87**, 1551, (1982).

P.Stubbe, H.Kopka, B.Thidé, H.Derblom J.Geophys.Res. **89**, 7523, (1984).

P.Stubbe, A.J.Stocker, F.Honary, T.R.Robinson, T.B.Jones J.Geophys.Res. **99**, 6233, (1994).

W.F.Utlaut J.Geophys.Res. **75**, 6402, (1970).

W.F.Utlaut, R.Cohen Science **174**, 245, (1971).

M.Vallinkoski, M.S.Lehtinen J.Atm.Terr.Phys. **52**, 675, (1990).

M.Vallinkoski, M.S.Lehtinen J.Atm.Terr.Phys. **52**, 665, (1990).

V.V.Vaskov, A.V.Gurevich Sov.Phys. JETP **42**, 91, (1975).

H.L.Zhou, J.Huang, S.P.Kuo Phys.of Plasmas **1**, 3044, (1994).